AN IMPEDANCE SPIROMETER

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To Dr. Allan V.N. Goodyer.

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I. Introduction

A. Impedance

When any two points have unequal voltages, a current will flow between these two points.

The magnitude of the current is a function of the medium in which the current flows and is governed by the following relationship:

$$Z = E/I \text{ where } \begin{array}{l} Z = \text{Impedance in ohms} \\ E = \text{E.M.f. in volts} \\ I = \text{current in amperes} \end{array}$$

In general, there is a complex relationship between E and I, so that Z is complex with two components: R, resistance; the X, reactance. The resistance is the energy dissipating component of Z. The reactance is the energy storing component of Z. When a circuit contains both resistance and reactance, the combined effect to the two is called impedance, symbolized by the letter Z. Impedance is thus a more general term than either resistance or reactance.

The reactance and resistance comprising an impedance may be connected in either series or paralled. When resistance and reactance are in series, the impedance of the circuit is

$$Z = \sqrt{R^2 + X^2}$$

The reactance may be either inductive, X_L, or capacitive, X_C. Therefore:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

However, in the human body at 100 Kc, the reactance is largely capacitive, thus $Z = \sqrt{R^2 + X_C} = \frac{1}{2\pi fc}$ where C = capacitance, and f = frequency.

B. Impedance Plethysmography

The Impedance Plethysmograph was designed to record changes in the volume of body segments. Original methods of recording the electrical impedance utilizing the Wheatstone Bridge technique were found to be unsatisfactory.[1] The Electrical Impedance Plethysmograph was designed in 1939 by Bagno and Nyboer and further modified and improved by Nyboer and his collaborators, Dubois and Nims.[2] Nyboer, Bagno and Nims, as part of the Yale Aeromedical Research Unit, demonstrated the empirical relationship of volume pulsation to electrical impedance in the finger.[3] Although Nyboer and his collaborators in the Yale Aeromedical Research Unit knew that the human body is not electrically homogenous, they postulated that since conductance is the reciprocal of the resistance, the change in volume becomes directly proportional to the change in electrical conductance. Further, they postulated that the capacitive reactance of all tissues was nearly equal and constituted only a small part of the total impedance. They assumed that an extremity could be considered as a series of parallel resistors

in which one, the volume of blood in the limb, was the only variable. Under these circumstances, the change in total resistance due to change in blood volume in the limb could be easily calculated.

However, the mathematical relationship between volume and the impedance or conductivity or the body segment that was formulated by these early investigators[2,3,4] has been challenged[5], and studies by Schwan[6] indicate that body tissue at the frequencies employed is not a homogenous conductor of electrical energy and that the capacitive reactance is of more importance than early investigators assumed it to be. Nevertheless, despite the theoretical objections that have been raised against the early claims, theories, and calculations of the early investigators, the Impedance Plethysmograph has been shown by many investigators[1,3,7,8] to be a very sensitive detector of pulsatile phenomena in small body segments.

To quote Brook and Cooper[7], "Since 1943, when Nyboer, Nims and Bagno submitted their circuit for an impedance plethysmograph to the National Research Council, any clinical potentialities which the instrument might have had were eclipsed by theoretical and experimental objections to original claims made for it. It would have been preferable had it not been called a plethysmograph or volume recorder, because it is a device which measures electrical conductivity. Conductivity, a reciprocal function of resistivity or impedance, is a distinct and measurable parameter of any conductor.

The problem of whether conductivity is quantitatively related to tissue volume, blood flow, or other properties of living tissue becomes an academic matter if the information derived from its empiric measurement is of value in its own right and in its own absolute units of measurement."

C. Impedance Plethysmography and Respiration

The effects of respiration upon impedance recording have been noted by many investigators. In 1935, Atzler[9] while recording impedance changes as a reflection of cardiac activity using anterior-posterior thoracic electrodes, noted the impedance changes due to respiration. He treated them as artifacts interfering with his study of cardiac activity and avoided recording them by requesting his subject to hold his breath.

Schaefer, et. al.[10] used an impedance system for recording respiration in animals and man with electrodes inserted subcutaneously in the chest wall.

Nyboer[1] made note of the effects of respiration: "The best pulse records are obtainable by recording during a respiration held in mid-position for 5 to 10 beats of the heart," and used his impedance plethysmograph to record respiration, and called attention to the large respiratory impedance changes. "At Yale Medical School, the impedance method was used to record continously the

respiration of small animals while in various stages of decompression and compression in experimental chambers. Respiration effects are large with respect to the volume pulse in small animals as judged from electrical impedance information."

Holzer, Polzer, and Marko[11] commented on the respiratory impedance changes as artifacts in their impedance plethysmographic studies of cardiac function.

Goldensohn and Zablow[12], using 10 Kc current passed between two EKG type electrodes placed on the wrists, demonstrated that the impedance changes were related to the volume of air moved, and demonstrated very similar waveforms recorded simultaneously with a bell spirometer and an Impedance Spirometer in six subjects. They further attempted to remove the artifact due to cardiac activity using a waveform generator triggered by the EKG to match and cancel the cardiac component and then used electrical filtering to reduce the remaining artifact. However, they did not attempt to quantitate the impedance readings with the bell spirometer readings.

Geddes, et. al.[13], attempting to establish the conditions which must be fulfilled for efficient utilization of the impedance technique for recording respiration, concluded that the frequency of the current used for measuring respiration should be somewhat higher than 10 Kc. Using both 10 Kc and 100 Kc, Geddes stated that

with leads across the chest, an impedance change of approximately 1% is typical of quiet respiration in man and animals.

Schaefer, et. al.,[10] using trans-thoracic electrodes on the cat, found a change of impedance of 5 ohms for each breath, superimposed on a basal resistance of 500 ohms.

Goldensohn and Zablow[12], using 10 Kc and 100 Kc applied to electrodes on the arms of human subjects, detected respiratory impedance changes of 1 ohm on a basal resistance of several hundred ohms. The basal resistance in each case represents the resting expiratory level.

No investigators, insofar as my review of the literature shows, have reported any data, or indications of the reproducibility of that data, showing the quantitative relationship of lung volumes and impedance readings.

D. Problems with present methods of spirometry

There has been need of a stable transducer for respiration which is easy to apply, reflects accurately the volume of air exchanged, and provides a minimum of restraint to the subject.

There are many methods of monitering respiration, but all suffer from some disadvantages which limit their application.

"Traditionally, respiration is recorded by one of four instruments: the pneumograph, the pneumotachograph, the spirometer, and the

negative pressure transducer. Difficulties encountered with the pneumograph include leaks in the air system and slippage on the body, along with the problem of locating the level where the maximum chest or abdominal expansion occurs, but the most serious defect of this device is the virtual impossibility of calibrating it in terms of the volumes of ventilation. Although the pneumotachograph and spirometer are excellent quantitative instruments which indicate air velocity and volume respectively, both require connection to the airway by a face mask or mouthpiece. While true volume is indicated, and the resistance to breathing are quite low, a considerable restriction is imposed on the subject. Recording intra-tracheal or intra-pleural pressure with a negative pressure transducer is only practical in a laboratory setting with anesthetized animals and even here the method is relatively uncalibratible."[13]

The technique of impedance spirometry offers the promise of freedom from many of the defects noted above. It is easy to apply and is relatively unencumbering to the subject. It has been shown[12] that recordings of trans-thoracic impedance change are identical in wave form and proportion to simultaneously recorded respiratory traces, the latter obtained with a bell spirometer.

No one has calibrated impedance readings with spirometer volumes to define the quantitative relationship between the two. If the quantitative relationship is defined, and impedance readings are

found to reproducible at given tidal volumes, the 'Impedance Spirometer' could become a useful tool for investigating respiratory phenomena.

II. Purpose of the Investigation

The purpose of this investigation was to define the quantitative relationship between the transthoracic electrical impedance change and the changes in lung volume that occur simultaneously during respiration.

III. Methods, Procedure and Equipment

A. Subjects

The four subjects used for the investigation were young healthy males between the ages of 20 and 23 years, without deformity of the thorax, respiratory disease or collection of fluid in the lungs, as determined by history and physical examination.

The height, weight, and chest circumference of the subjects are given in table I.

Table No. I

SUBJECT	HEIGHT	WEIGHT	CHEST CIRCUMFERENCE, EXPIRATION
I	6' 1"	206 lbs.	$41\frac{1}{4}$ "
II	5' 8"	195 lbs.	38 "
III	6'	185 lbs.	37 "
IV	5'10"	186 lbs.	38 "

B. Air Measurements

The subjects wore a Bennett type A face mask, secured to the face with rubber straps, and connected to two valves. One valve was connected to a meter that indicated inspired air volume and was utilized by the subject as a rough guide to regulate the depth of respiration to within approximately 100 cc. The other valve

allowed expired air to pass into a spirometer which measured expired air volume. The spirometer was an American Meter Company meter prover of the type used to calibrate gas meters and clinical spirometers. The meter prover was connected through an air volume transducer to a Sanborn 150-1600 D.C. Preamplifier and ECG Recorder #158-100 B. The arrangement of equipment appears in Fig. 1.

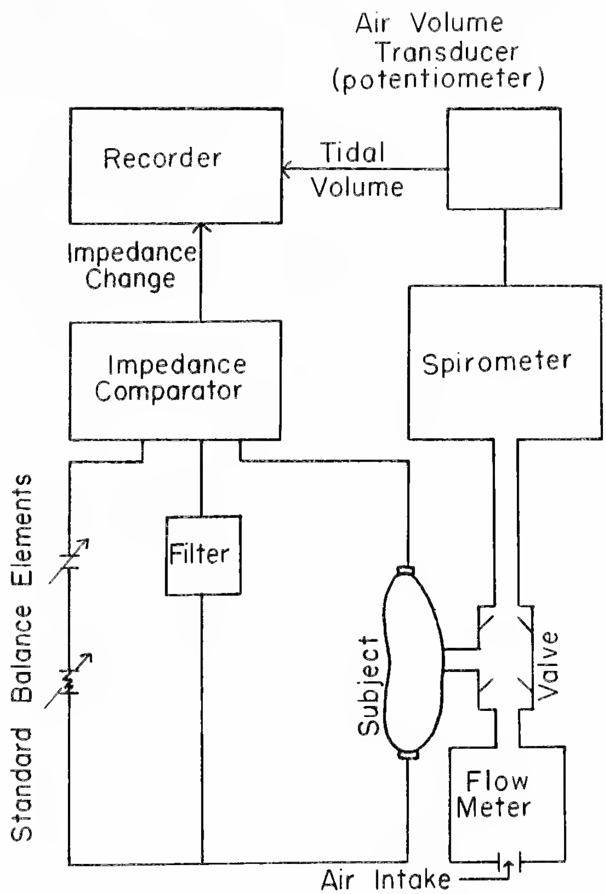

Fig. 1. Arrangement of Equipment

C. Comparator and Lead Circuitry

See Figure 1 for arrangement of the recorder, comparator, and lead circuitry. The electrical impedance was determined with a General Radio type 1605 A Impedance Comparator. One lead was connected to a General Radio 1419 A decade capacitor and a General Radio 1432 N decade resistor assembled in series. Two other leads were used with one electrode on each lead. The common lead passed through a 10 Kc high pass filter and this lead and accompanying electrode were always attached to the subject's right side. The third lead and electrode were always applied to the subjects left side. The comparator was operated at a frequency of 100 Kc. The comparator was set and operated at a sensitivity difference such that a full scale deflection of the recording pens was equal to 3% of the total impedance at which the comparator was balanced. The comparator was connected to the Sanborn Recorder described above.

D. Electrodes

1. Electrode placement

Eighty-one preliminary electrode placement trials were conducted on two subjects. Based on these trials, the best position for electrode placement was the 7th intercostal space in the mid-axillary line, with electrodes applied bilaterally in this position.

When transthoracic impedance recordings are made, two intrathoracic phenomena affect the trace. The largest effect is due to respiration. Superimposed on this is a lesser, cardiac effect. There was nothing to suggest that the electrode position eventually chosen was any more accurate than any other. It was chosen because of the large respiratory impedance trace and small cardiac impedance artifact that occurred at this position. The desirability of a minimal cardiac artifact is obvious. Experiments reported by Geddes, et. al.[13] since these electrode placement trials were completed have tended to confirm the selection of the above mentioned site as the optimal position for electrode placement for recordings of respiration.

2. Electrode size and composition

During preliminary experiments to determine the type of electrodes to be used, electrodes from ½" to 3" in diameter were examined. Electrodes of conducting cloth and stainless steel mesh, both used with electrode paste, were considered. The composition of the electrode did not appear to be a factor in determining the height or wave shape of the impedance change recording.

It was observed that the larger the surface area of the electrode in contact with the skin, the larger the amplitude of the change of impedance recording. This phenomena is probably related to the resistance encountered at the skin-electrode contact point,

as it appears that this resistance is inversely related to the area of the electrode.

The larger electrodes were more difficult to apply, and tended to move more during respiration, changing the area of skin contact and measured impedance. Electrodes 1" in diameter proved to be the largest electrode that gave satisfactory results.

Throughout the experiments 1" diameter round cup stainless steel mesh electrodes were used. One electrode appears in Figure 2.

Figure 2. 1" cup electrode used in the experiments.

3. Application of Electrodes

The electrodes were filled with Sanborn Redux Electrode Paste #651-1008 and applied to the skin without any preliminary sanding or rubbing of the skin. Electrodes were taped to the skin with Minnesota Mining and Manufacturing transparent surgical tape #525. No recordings were made until ten minutes after the electrodes were applied.

E. Experimental Conditions and Procedure

Experiments were performed in an air conditioned room with temperature held constant at 75°F. $\pm 1^{\circ}$.

Subjects were seated at a table with their hands clasped and resting on the table. They sat upright, resting their backs against the back of the chair. After applying the electrodes and face mask and balancing the comparator, the subject was instructed to breathe starting with a nominal tidal volume of approximately 250 cc. for ten to fifteen respirations, setting his own respiratory rate. Upon command from the experimenter, the subject would increase his tidal volume by approximately 250 cc. increments up to 1500 cc., with up to fifteen respirations at each increment. Then the same procedure was repeated from 1500 cc. up, in 500 cc. increments until the subject's vital capacity was reached. Throughout the

experiment the subject set his own respiratory rate. Recordings of the tidal volume and impedance changes and phase angle changes were made throughout the entire procedure.

The application of electrodes and recording of tidal volume and impedance change was repeated three times at widely separated intervals of from one to twelve days, with each of the four subjects, thus giving three complete sets of data for each subject. This procedure was followed in an effort to determine the reproducibility of the data obtained.

F. Calculations

When the comparator was balanced, the resistance and capacitance required to balance it were read from the decade boxes and comparator, recorded, and the following calculations were performed with a slide rule:

X_c = Capacitive reactance in ohms.

$$X_c = \frac{1}{2\pi fC} = \frac{1.59}{C} \text{ at a frequency of 100 Kc or 0.1 Mc.}$$

C is in μfarads

Then the impedance was computed:

$$Z = \sqrt{R^2 + X_c^2}$$

This gives the total impedance in ohms at which the comparator was balanced. However, the impedance change that accompanies respiration

comprises only a small fraction of the total impedance, and is superimposed on it when the comparator is balanced.

The total impedance at which the comparator was balanced was multiplied by the sensitivity at which the comparator was set.

$$Z \text{ total, balanced} \times .03 = Z_{\text{full scale deflection}}$$

This gives the impedance in ohms of a full scale deflection of the recording pens, and needles of the meters on the comparator and recorder. Since they were calibrated, dividing this impedance by 50,

$$\frac{Z_{\text{full scale deflection}}}{50} = Z_s$$

giving the impedance in number of ohms per square (Z_s) on the recording paper. Therefore the impedance (Z) for any respiratory recording could be calculated by multiplying the height of the wave in number of squares (s) by the number of ohms per square (Z_s).

$$Z = s \times Z_s$$

The **spirometer** readings of expired air were recorded so that a deflection of the recording pens of 50 squares on the recording paper was equal to 3.125 liters of expired air. Therefore dividing 3.125 by 50 gave 62.5 cc of expired air per square.

$$\frac{3.125}{50} = 62.5$$

The number of cc.'s of air per expiration were computed by counting the number of squares or fractions thereof and multiplying this by 62.5. See Figure 3.

T. V.

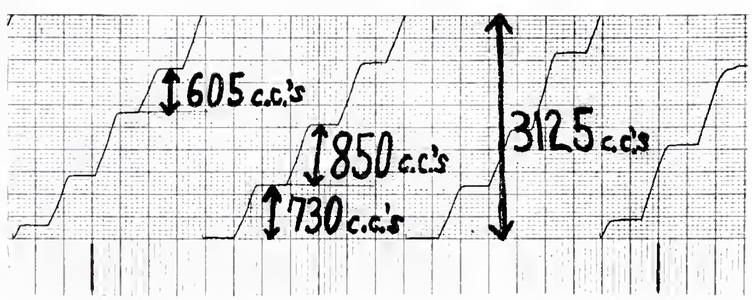

Figure 3. Examples of the recording of expiratory tidal volume (T.V.), calculated from the recorder pen deflection of 62.5 cc per scale division of the record.

IV. Results

Typical recordings of the impedance and corresponding tidal volume are shown in Figure 4. Bridge balance resistance and capacitance values were centered around 210 ohms and 0.030 microfarads for all trials.

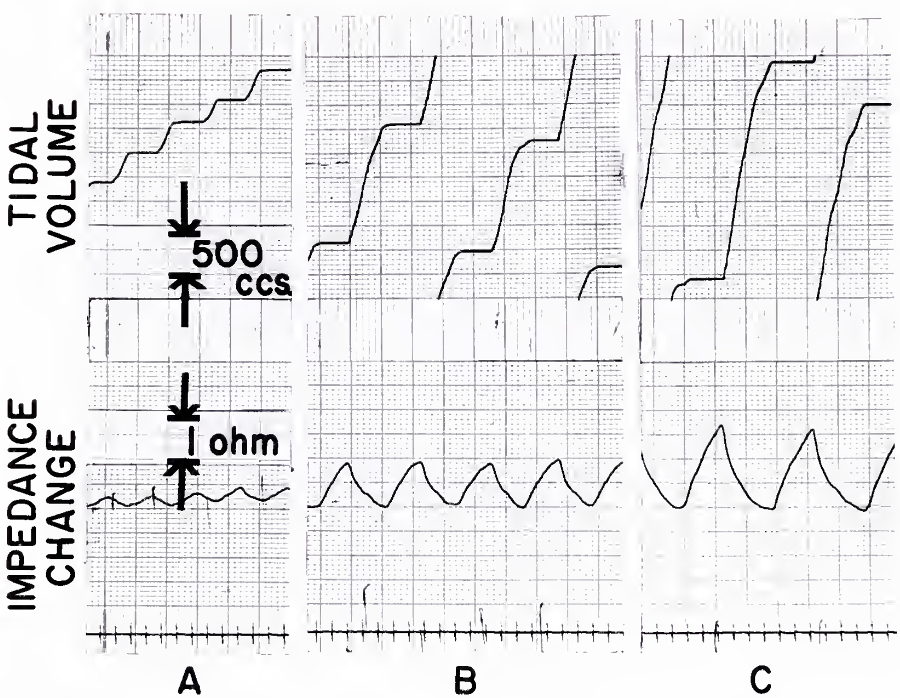

Figure 4. Tidal volume and impedance change.
Subject I, Trial 2, August 4, 1961

The results indicate that for the four subjects there is an average change in tidal volume of 816 cc. per one ohm change in impedance, measured at 100 Kilocycles/sec. Figure 5 shows the means of all the readings, 1063 in number, on all subjects averaged, in 250 cc. and 500 cc. tidal volume intervals. It also shows the linear character and standard deviations of these mean values. These data are also presented in Table II. These means suggest a relationship that can be best represented by a straight line. See Figure 5.

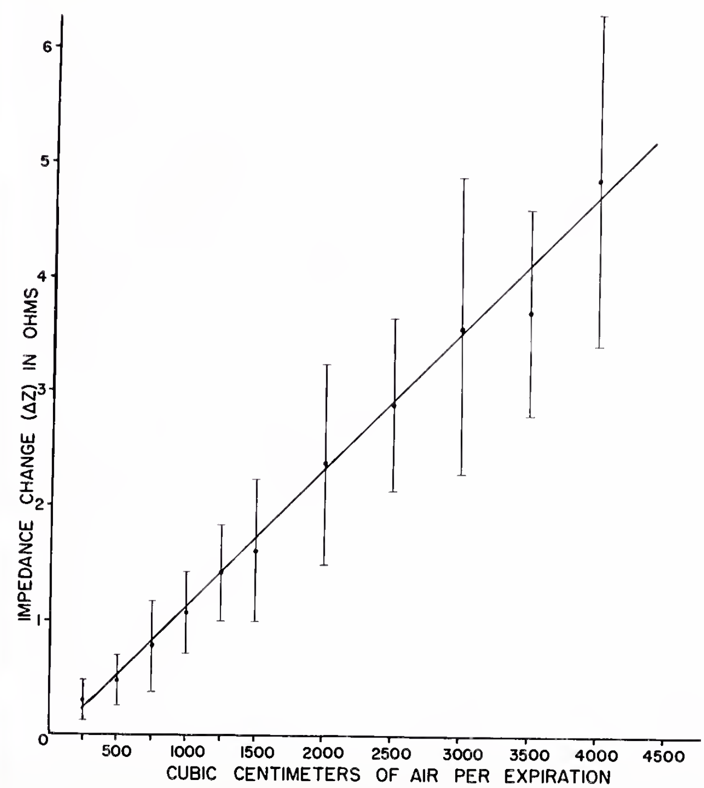

Figure 5. Mean values of impedance change versus tidal volume, and standard deviations of the means, for four subjects.

Table No. II

Mean Values of impedance change versus tidal volume for four subjects.

Tidal volume plus/minus 30 cc's	Mean Impedance change in ohms	Standard Deviation of Impedance change in ohms	% the S.D. is of Mean Impedance
250	0.308	0.171	55%
500	0.467	0.217	46%
750	0.785	0.392	49%
1000	1.084	0.360	33%
1250	1.42	0.176	12%
1500	1.62	0.636	39%
2000	2.39	0.883	37%
2500	2.91	0.755	26%
3000	3.58	1.280	36%
3500	4.13	0.900	22%
4000	4.90	1.435	29%

The standard deviation of the impedance change tended to be quite large, varying from approximately 50% of the magnitude of the impedance change for low tidal volumes to approximately 30% for larger tidal volumes.

The curves in Figures 6 through 9 were drawn by eye to best indicate the results for each trial. The data on the individual subjects, with the percentage error that may be encountered in predicting tidal volume from impedance readings, and in predicting ohms change from tidal volumes, are represented in Table III.

To read the precentage error that may be expected by predicting tidal volumes from impedance changes, start with column D and read back to column A. For example, Subject II, at an impedance change of 0.275 ohms averaged 500 cc. tidal volume for the 3 trials. However, the actual tidal volumes observed ranged from 425 cc. to 575 cc., so that a ±15% error in tidal volume could occur if one predicted a 500 cc tidal volume from a 0.275 ohm impedance change.

The errors in predicting impedance change from tidal volumes may be obtained from Table III by reading column C through Column F.

Table III

Subject	Approx. % error in predicting T.V.	OBSERVED Range of Tidal Volumes cc.	PREDICTED, Based on 3-trial averages T.V. cc	PREDICTED, Based on 3-trial averages Z change ohms	OBSERVED range of Impedance Change ohms	Approx. % error in predicting Z change
column	A	B	C	C	E	F
I	±20%	375-600	500	0.35	0.25-0.50	±36%
	± 25%	750-1225	1000	0.85	0.60-1.20	±35%
	± 17%	2600-3600	3000	2.90	2.50-3.60	±19%
II	±15%	425-575	500	0.275	0.24-0.325	±15%
	± 13%	925-1200	1000	0.75	0.60-0.90	±20%
	± 11%	2650-3300	3000	3.45	3.10-4.10	±14%
III	± 10%	450-550	500	0.50	0.46-0.54	±8%
	± 25%	800-1300	1000	1.40	1.10-1.95	±26%
	±25%	2250-3750	3000	4.40	3.20-6.20	±34%
IV	± 25%	450-700	500	0.90	0.70-1.05	±20%
	± 15%	850-1125	1000	1.70	1.50-2.00	±15%
	± 4%	2800-3050	3000	4.60	4.25-4.90	±7%

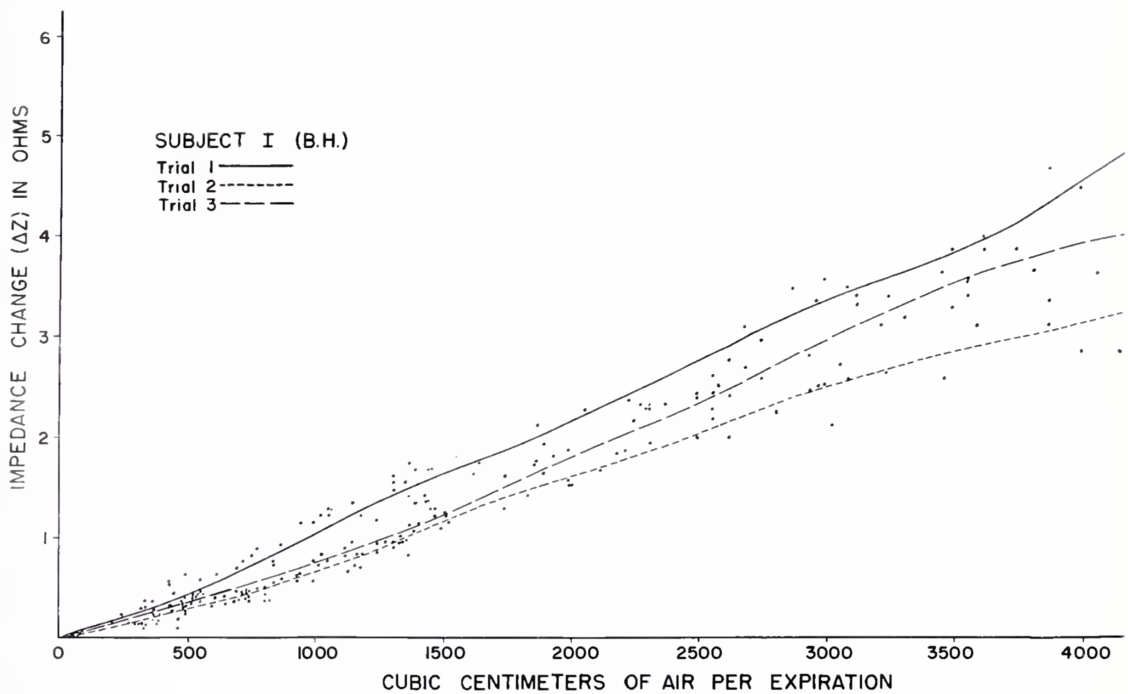

Figure 6. Impedance change as a function of tidal volume, Subject I, trials 1-3.

Subject I had a three trial average impedance change of approximately one ohm per 1000 cc. of tidal volume.

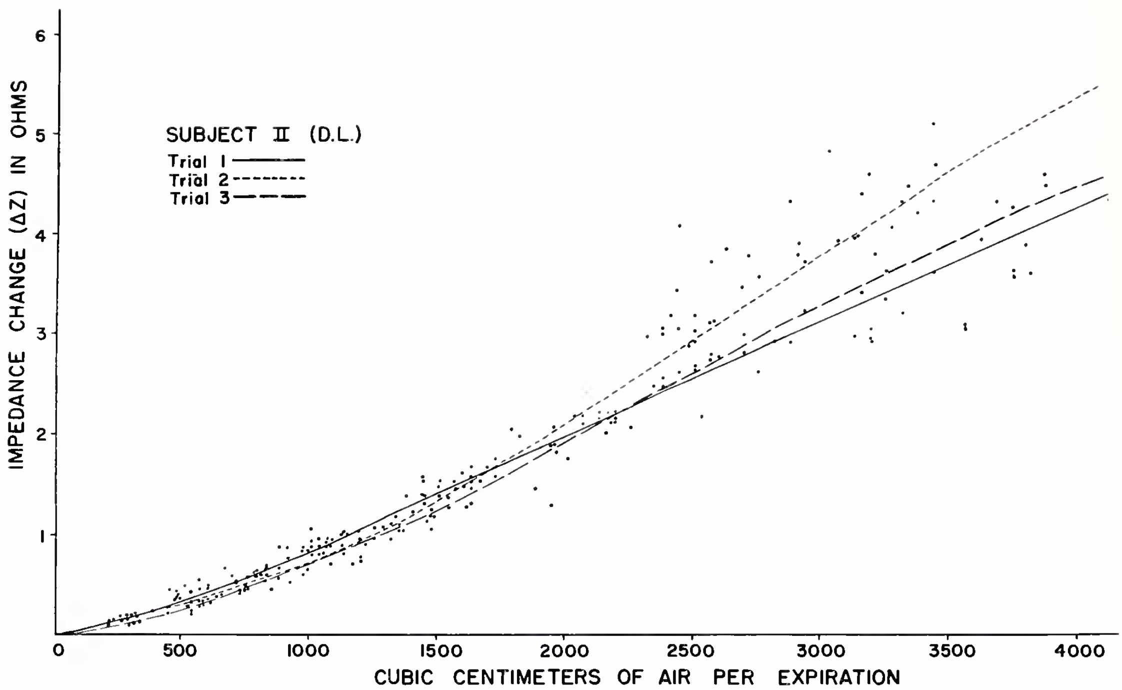

Figure 7. Impedance change as a function of tidal volume, Subject II, trials 1-3.

Subject II has a three trial average impedance change of approximately one ohm per 800 cc. of tidal volume.

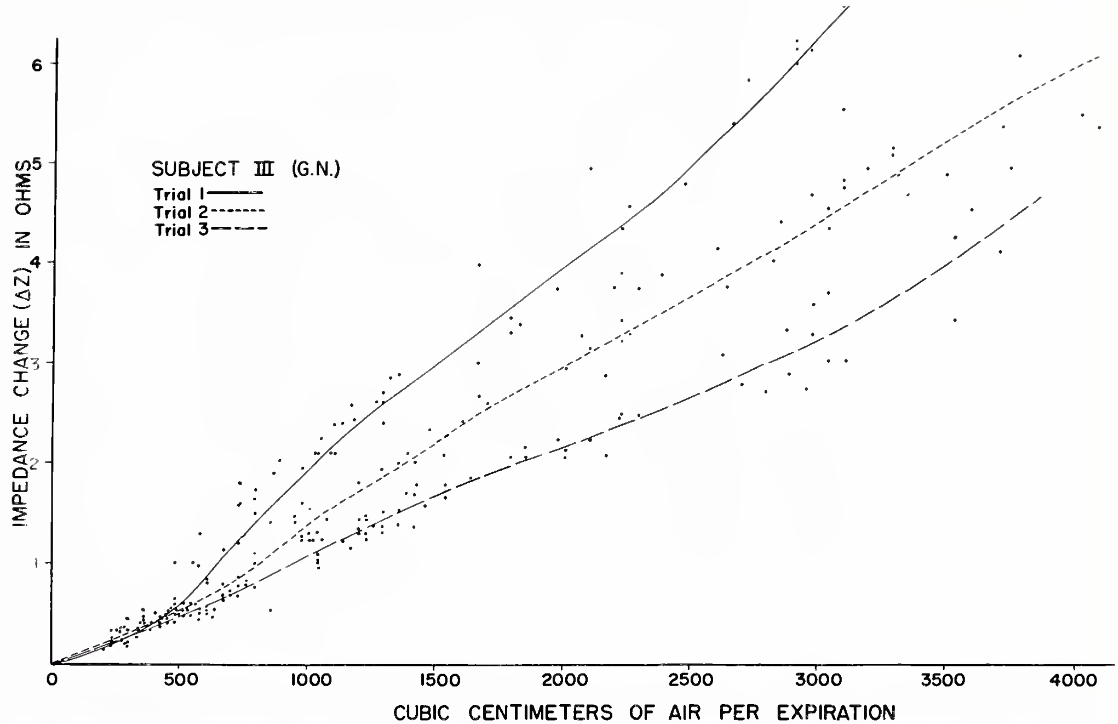

Figure 8. Impedance change as a function of tidal volume, Subject III, trials 1-3.

Subject III has a three tiral average impedance change of approximately one ohm per 640 cc. of tidal volume.

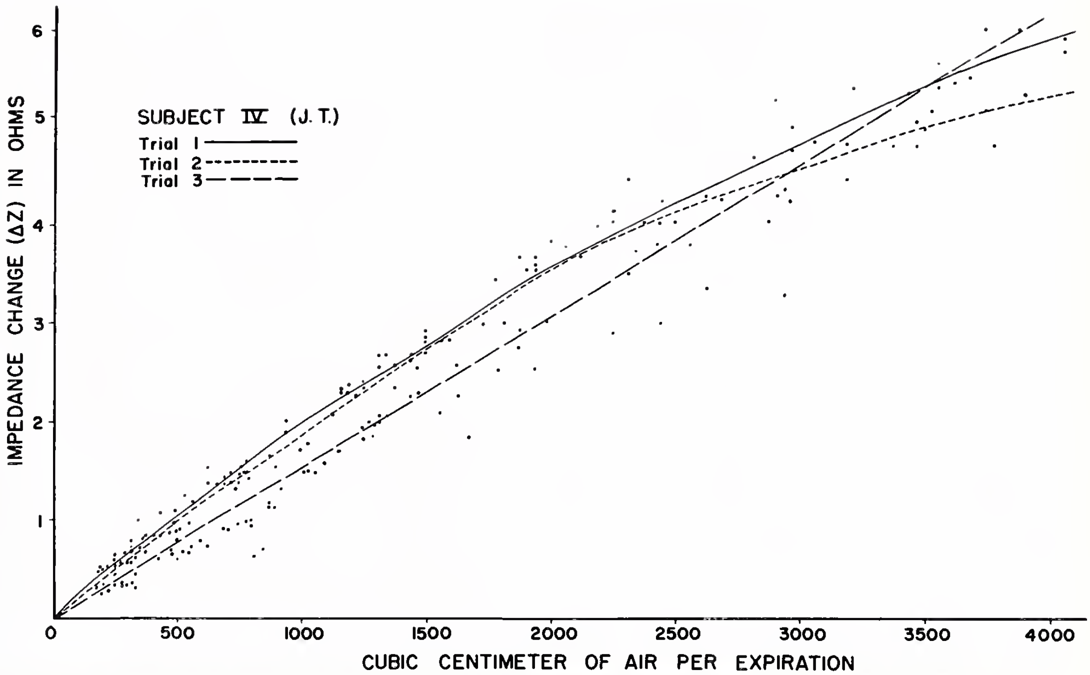

Figure 9. Impedance change as a function of tidal volume, Subject IV, trials 1-3.

Subject IV has a three trial average impedance change of approximately one ohm per 690 cc. of tidal volume.

V. Summary and Discussion

The quantitative relationship between trans-thoracic impedance changes and the changes in lung volume that occur simultaneously during respiration were investigated. In four young healthy male subjects using 1 inch electrodes applied bilaterally to the 7th intercostal space in the midaxillary line, and at a bridge frequency of 100 Kilocycles:

1) There was an average of 1 ohm change in impedance per 816 cubic centimeters of tidal volume, for all subjects, all trials and tidal volumes between 250 and 4000 cc.

2) There is a linear relationship between transthoracic impedance change and tidal volume when the data from all the subjects and all trials is utilized. See Figure 5.

3) The data from the individual subject trials indicates significant variation both between subjects, and between trials on each subject with regard to the impedance change per given tidal volume. See Tables II and III and Figures 5 through 9.

4) Until more refined methods of determining the relationship of transthoracic impedance to pulmonary tidal volume are found which do not produce the variability in results obtained above, the usefulness of this method to measure pulmonary tidal volume is probably limited to situations where only a minimum of apparatus may be attached to the subject and/or a more precise instrumentation cannot be attached to the upper airway.

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